

# Possible $D\bar{D}$ and $B\bar{B}$ Molecular states in a chiral quark model

M.T. Li,<sup>1,2</sup> W.L. Wang,<sup>1,2</sup> Y.B. Dong,<sup>1,2</sup> and Z.Y. Zhang<sup>1,2</sup>

<sup>1</sup>*Institute of High Energy Physics, CAS, P.O. Box 918-4, Beijing 100049, China*

<sup>2</sup>*Theoretical Physics Center for Science Facilities (TPCSF), CAS, Beijing 100049, China*

We perform a systematic study of the bound state problem of  $D\bar{D}$  and  $B\bar{B}$  systems by using effective interaction in our chiral quark model. Our results show that both the interactions of  $D\bar{D}$  and  $B\bar{B}$  states are attractive, which consequently result in  $I^G(J^{PC}) = 0^+(0^{++})$   $D\bar{D}$  and  $B\bar{B}$  bound states.

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## I. INTRODUCTION

Since the discovery of X(3872), many X, Y, and Z exotic states have been reported. These hadrons have ever been explained as molecules, tetraquarks, hybrids *et al.* because they can't be interpreted as simple quarkoniums. In our previous chiral quark model calculation [1], it is found that the newly observed hadrons, such as  $Z_b(10610)$ ,  $Z_b(10650)$ , X(3872) and Y(3940), might be assigned as the  $B\bar{B}^*$ ,  $B^*\bar{B}^*$ ,  $D\bar{D}^*$  and  $D^*\bar{D}^*$  bound states. These results stimulate our further interest in studying their analogues, i.e. the systems of  $D\bar{D}$  and  $B\bar{B}$ .

So far, several works have been done to calculate the  $D\bar{D}$  and  $B\bar{B}$  states [2–11]. Valcarce et al. [2–4] considered the  $D\bar{D}$  coupled to charmonium-light two-meson systems, like  $J/\psi\omega$  channel, and concluded that the  $0^+(0^{++})$   $D\bar{D}$  is the only possible bound state. Ke *et al.* [5] supported the existence of  $0^+(0^{++})$   $D\bar{D}$  and  $B\bar{B}$  molecules in the Bethe-Salpeter framework. In one-meson-exchange model, Liu et al. [6–8] calculated the binding energies of  $D\bar{D}$  and  $B\bar{B}$  systems. Meanwhile, Zhang *et al.* [9] got such molecules:  $B\bar{B}$  of  $10580 \pm 100$  MeV and  $D\bar{D}$  of  $3760 \pm 100$  MeV in QCD sum rule calculation on the quark level. Their results are consistent with Wong's prediction in a two-gluon-exchange model [10]. On the contrary, Yang *et al.* [11] argued that in color-singlet channel  $D\bar{D}$  and  $B\bar{B}$  molecules didn't exist. To sum up the above calculations, one sees that the existence and properties of the possible  $D\bar{D}$  and  $B\bar{B}$  molecular states are presently model dependent. Further theoretical investigations are expected to be significant.

In this paper, we perform a dynamical study of the  $D\bar{D}$  and  $B\bar{B}$  systems with isospin  $I = 0$  and 1 in our chiral quark model by using the effective interaction. The chiral quark model was built in such a way that the chiral symmetry is restored by introducing the coupling between quark field and Goldstone bosons and the constituent quark mass is obtained as a consequence of the spontaneous vacuum symmetry breaking. In our chiral SU(3) quark model, one-gluon-exchange (OGE) governs the short range and scalar chiral field as well as pseudoscalar chiral field are induced for restoring the chiral symmetry. As is well known, the short range mechanism of the quark-quark interaction mechanism is still an open problem, and people is debating whether the OGE plays a dominating role in the short range, or vector meson exchange does, or both of them are important. Thus to examine the short range mechanism, we developed our chiral SU(3) quark model into the extended chiral SU(3) quark model in which the vector meson exchange is included. During the past few years, both the chiral SU(3) quark model and the extended chiral SU(3) quark model have appeared to be quite successful in reproducing the spectra of the baryon ground states, the binding energy of deuteron, the nucleon-nucleon ( $NN$ ), kaon-nucleon ( $KN$ ) scattering phase shifts, and the hyperon-nucleon ( $YN$ ) cross sections [12–16].

Recently, the chiral quark model was also employed to study the interactions and structures of the heavy-quark systems by using the Resonating Group Method (RGM) [17–19]. Here we will use the same chiral quark model to study the  $D\bar{D}$  and  $B\bar{B}$  interactions. Different from the RGM method, we have derived analytical forms of the total interaction potentials between the two S-wave heavy mesons as discussed in Refs. [1, 20]. We thoroughly investigate the possible bound states of  $D\bar{D}$  and  $B\bar{B}$  systems by solving the Schrödinger equation with our analytical potentials between the two clusters, anticipating that this method would give a more accurate description of the short-range interaction between the two clusters than the RGM does.

The paper is organized as follows. In section II, the framework of our chiral quark model is briefly introduced, and the analytical forms of the effective interaction potentials between the two S-wave heavy mesons under our chiral quark model are given. The bound state solutions for the  $D\bar{D}$  and  $B\bar{B}$  systems are shown and discussed in Sec. III. Finally, a short summary is given in Sec. IV.

## II. FORMULATION

In our chiral SU(3) quark model, we consider the scalar meson-exchange interaction and the pseudoscalar meson-exchange interaction which are induced from quark-chiral field interaction, OGE interaction and confinement potential. Moreover, in our extended chiral SU(3) quark model, we also take the vector meson-exchange interactions into account which would almost replace the OGE interaction in the original chiral SU(3) quark model [14]. In principle, the axial vector meson exchange should also be included to keep the chiral symmetry. However, as the axial mesons are much heavier than the chiral symmetry breaking scale, they are simply omitted in our calculation.

The framework of our models has been discussed extensively in the literature [12–19, 21–24]. In this work, different from the RGM calculation, the internal kinetic energies and the internal interactions of each meson are not necessary to be calculated. As a result, the Hamiltonian of relative motion in this work reads

$$H = T_{rel} + V_{eff}, \quad (1)$$

where  $T_{rel}$  is the kinetic energy operator of the relative motion between the two mesons, and  $V_{eff}$  is the effective interaction potential derived from the quark-quark (quark-antiquark) interaction between two mesons by integrating the internal coordinates  $\vec{\xi}_1$  and  $\vec{\xi}_2$  of two mesons:

$$V_{eff} = \sum_{ij} \int \varphi_1^*(\vec{\xi}_1) \varphi_2^*(\vec{\xi}_2) V(\vec{r}_{ij}) \varphi_1(\vec{\xi}_1) \varphi_2(\vec{\xi}_2) d\vec{\xi}_1 d\vec{\xi}_2, \quad (2)$$

while  $\varphi_1(\vec{\xi}_1)$  and  $\varphi_2(\vec{\xi}_2)$  are the intrinsic wavefunctions of two S-wave mesons, taken as one-Gaussian form:

$$\varphi(\vec{\xi}) = \left(\frac{\mu\omega}{\pi}\right)^{3/4} e^{-\frac{\mu\omega}{2}\xi^2}. \quad (3)$$

Here,  $\mu$  is the reduced mass of the two quarks inside each meson and  $\omega$  is the harmonic-oscillator frequency of the meson intrinsic wavefunction.  $V(\vec{r}_{ij})$  in Eq. 2 represents the interactions between the  $i$ -th light quark or antiquark in the first meson and the  $j$ -th light quark or antiquark in another.

In this work, because there is no color-interrelated interaction between the two color-singlet clusters, such as OGE interaction and confinement potential, we only consider the meson-exchange interactions. Therefore, for the chiral SU(3) quark model

$$V(\vec{r}_{ij}) = \sum_{a=0}^8 V^{\sigma_a}(\vec{r}_{ij}) + \sum_{a=0}^8 V^{\pi_a}(\vec{r}_{ij}), \quad (4)$$

and for the extended chiral SU(3) quark model

$$V(\vec{r}_{ij}) = \sum_{a=0}^8 V^{\sigma_a}(\vec{r}_{ij}) + \sum_{a=0}^8 V^{\pi_a}(\vec{r}_{ij}) + \sum_{a=0}^8 V^{\rho_a}(\vec{r}_{ij}), \quad (5)$$

with  $V^{\sigma_a}(\vec{r}_{ij})$  and  $V^{\pi_a}(\vec{r}_{ij})$  being the interactions respectively induced from scalar meson exchange and pseudoscalar meson exchange.  $V^{\rho_a}(\vec{r}_{ij})$  indicates the vector meson exchange interaction. For quark-quark (antiquark-antiquark) interaction,  $V^{\sigma_a}(\vec{r}_{ij})$ ,  $V^{\pi_a}(\vec{r}_{ij})$  and  $V^{\rho_a}(\vec{r}_{ij})$  have been described in detail in Refs. [1, 12–19, 21–24]:

$$V^{\sigma_a}(\vec{r}_{ij}) = -C(g_{ch}, m_{\sigma_a}, \Lambda) X_1(m_{\sigma_a}, \Lambda, r_{ij}) (\lambda_i^a \lambda_j^a), \quad (6)$$

$$V^{\pi_a}(\vec{r}_{ij}) = C(g_{ch}, m_{\pi_a}, \Lambda) \frac{m_{\pi_a}^2}{12m_i m_j} X_2(m_{\pi_a}, \Lambda, r_{ij}) \times (\sigma_i \cdot \sigma_j) (\lambda_i^a \lambda_j^a), \quad (7)$$

$$V^{\rho_a}(\vec{r}_{ij}) = C(g_{chv}, m_{\rho_a}, \Lambda) \left[ X_1(m_{\rho_a}, \Lambda, r_{ij}) + \frac{m_{\rho_a}^2}{6m_i m_j} \times \left( 1 + \frac{f_{chv}}{g_{chv}} \frac{m_i + m_j}{M_N} + \frac{f_{chv}^2}{g_{chv}^2} \frac{m_i m_j}{M_N^2} \right) \right. \\ \left. \times X_2(m_{\rho_a}, \Lambda, r_{ij}) (\sigma_i \cdot \sigma_j) \right] (\lambda_i^a \lambda_j^a), \quad (8)$$

with

$$C(g_{ch}, m, \Lambda) = \frac{g_{ch}^2}{4\pi} \frac{\Lambda^2}{\Lambda^2 - m^2} m, \quad (9)$$

$$X_1(m, \Lambda, r_{ij}) = Y(mr_{ij}) - \frac{\Lambda}{m} Y(\Lambda r_{ij}), \quad (10)$$

$$X_2(m, \Lambda, r_{ij}) = Y(mr_{ij}) - \left(\frac{\Lambda}{m}\right)^3 Y(\Lambda r_{ij}), \quad (11)$$

$$Y(x) = \frac{1}{x} e^{-x}, \quad (12)$$

where  $\lambda^a$  is the Gell-Mann matrix in flavor space, and  $\Lambda$  is the cutoff mass which indicates the chiral symmetry breaking scale.  $m_i$  and  $m_j$  are the masses of the  $i$ -th light quark or antiquark in the first meson and the  $j$ -th light quark or antiquark in another respectively, while  $m_{\sigma_a}$ ,  $m_{\pi_a}$  and  $m_{\rho_a}$  in Eqs. 6, 7, and 8 are the masses of the scalar nonets, the pseudoscalar nonets and the vector nonets, respectively.  $M_N$  in Eq. 8 is a mass scale usually taken as the mass of nucleon [14].  $g_{ch}$  is the coupling constants for the scalar and pseudoscalar nonets.  $g_{chv}$  and  $f_{chv}$  are the coupling constants for the vector coupling and tensor coupling of vector nonets, respectively.

In  $D\bar{D}$  and  $B\bar{B}$  systems, we don't consider the one-meson exchange interactions between two heavy quarks or between one heavy quark and one light quark, because if one wants to include the interactions related to heavy quarks, the heavy meson-exchanges as well as light meson exchanges must be also considered simultaneously, and these interactions are beyond our SU(3) models. By using the method described in Refs. [1, 20] and integrating the internal coordinates of two mesons, we get the analytical effective interaction potentials between two mesons  $D\bar{D}(B\bar{B})$  as

$$V_{eff}(\vec{R}) = \sum_{a=0}^8 V_{q\bar{q}}^{\sigma_a}(\vec{R}) + \sum_{a=0}^8 V_{q\bar{q}}^{\pi_a}(\vec{R}) + \sum_{a=0}^8 V_{q\bar{q}}^{\rho_a}(\vec{R}),$$

with

$$V_{q\bar{q}}^{\sigma_a}(\vec{R}) = -G_{\sigma_a} C(g_{ch}, m_{\sigma_a}, \Lambda) X_{1q\bar{q}}(m_{\sigma_a}, \Lambda, R) (\lambda_q^a \lambda_{\bar{q}}^a), \quad (13)$$

$$V_{q\bar{q}}^{\pi_a}(\vec{R}) = G_{\pi_a} C(g_{ch}, m_{\pi_a}, \Lambda) \frac{m_{\pi_a}^2}{12m_q m_{\bar{q}}} X_{2q\bar{q}}(m_{\pi_a}, \Lambda, R) \times (\sigma_q \cdot \sigma_{\bar{q}}) (\lambda_q^a \lambda_{\bar{q}}^a), \quad (14)$$

$$V_{q\bar{q}}^{\rho_a}(\vec{R}) = G_{\rho_a} C(g_{chv}, m_{\rho_a}, \Lambda) \left[ X_{1q\bar{q}}(m_{\rho_a}, \Lambda, R) + \frac{m_{\rho_a}^2}{6m_q m_{\bar{q}}} \left( 1 + \frac{f_{chv}}{g_{chv}} \frac{m_q + m_{\bar{q}}}{M_N} + \frac{f_{chv}^2}{g_{chv}^2} \frac{m_q m_{\bar{q}}}{M_N^2} \right) \right. \\ \left. \times X_{2q\bar{q}}(m_{\rho_a}, \Lambda, R) (\sigma_q \cdot \sigma_{\bar{q}}) \right] (\lambda_q^a \lambda_{\bar{q}}^a). \quad (15)$$

Here,  $G_{\sigma_a, \pi_a, \rho_a}$  is the  $G$ -parity of the exchanged meson, and  $\vec{R}$  is the relative coordinate between two different mesons, namely, the relative coordinate between the two centers-of-mass coordinates of the two mesons, and

$$X_{1q\bar{q}}(m, \Lambda, R) = Y_{q\bar{q}}(mR) - \frac{\Lambda}{m} Y_{q\bar{q}}(\Lambda R), \quad (16)$$

$$X_{2q\bar{q}}(m, \Lambda, R) = Y_{q\bar{q}}(mR) - \left(\frac{\Lambda}{m}\right)^3 Y_{q\bar{q}}(\Lambda R). \quad (17)$$

In above equations,  $m_q$  and  $m_{\bar{q}}$  are masses of the light quark and antiquark, respectively. The modified Yukawa term in Eqs. 16 and 17 reads

$$Y_{q\bar{q}}(mR) = \frac{1}{2mR} e^{\frac{m^2}{4\beta}} \left\{ e^{-mR} \left\{ 1 - \operatorname{erf} \left[ -\sqrt{\beta} \left( R - \frac{m}{2\beta} \right) \right] \right\} - e^{mR} \left\{ 1 - \operatorname{erf} \left[ \sqrt{\beta} \left( R + \frac{m}{2\beta} \right) \right] \right\} \right\}. \quad (18)$$

Here,

$$\beta = \frac{\mu_{q\bar{Q}} \mu_{Q\bar{q}} \omega}{\mu_{q\bar{Q}} \left( \frac{m_Q}{m_Q + m_{\bar{q}}} \right)^2 + \mu_{Q\bar{q}} \left( \frac{m_{\bar{Q}}}{m_q + m_Q} \right)^2}. \quad (19)$$

$m_Q$  and  $m_{\bar{Q}}$  are masses of the heavy quark and antiquark respectively, and  $\mu_{qQ} = \frac{m_q m_Q}{m_q + m_Q}$ .

There are some necessary parameters in the potentials of our chiral quark model. In this work, we adopt the parameters determined in our previous works [12–19, 21–23]. The up/down quark mass  $m_q$  is fitted as the nucleon

mass and taken as  $M_N/3 \sim 313$  MeV. The coupling constant for the scalar and pseudoscalar chiral fields  $g_{ch} = 2.621$  is fixed by the relation of

$$\frac{g_{ch}^2}{4\pi} = \frac{9}{25} \frac{g_{NN\pi}^2}{4\pi} \frac{m_u^2}{M_N^2},$$

with  $g_{NN\pi}^2/4\pi = 13.67$  determined from experiments.

In our extended chiral SU(3) quark model, the vector coupling constant  $g_{chv}$  and tensor coupling constant  $f_{chv}$  in Eqs. 8, 15 are fitted by the mass difference between  $N$  and  $\Delta$ , when the strength of the OGE is taken to be almost zero. When the tensor coupling is neglected,  $g_{chv} = 2.351$  and  $f_{chv} = 0$ ; when the tensor coupling is considered,  $g_{chv} = 1.973$  and  $f_{chv} = 1.315$ . The harmonic-oscillator frequency  $\omega$ , equal to  $1/(m_u b_u^2) = 1/(m_c b_c^2)$  where  $b_u$  is fitted by the  $N - N$  scattering phase shifts, is taken as  $2.522 fm^{-1}$  in the chiral SU(3) quark model and  $3.113 fm^{-1}$  in the extended chiral SU(3) quark model. In our calculation, the masses of the mesons are taken from the PDG [25], except the  $\sigma$  meson, which does not have a well-defined value. Here  $m_\sigma$  is obtained by fitting the binding energy of the deuteron [14]. It is  $m_\sigma = 595$  MeV in our chiral SU(3) quark model, 535 MeV for neglecting tensor coupling and 547 MeV for considering tensor coupling in our extended chiral SU(3) quark model. The cutoff mass  $\Lambda$  is the chiral symmetry breaking scale and taken as 1100 MeV as a convention.

The remaining parameters to be determined are the heavy quark masses  $m_c$  and  $m_b$ . In our work, we find that the final results are not sensitive to the variation of the heavy quark masses, and we take  $m_c = 1430$  MeV [26] and  $m_b = 4720$  MeV [27] as typical values.

### III. NUMERICAL SOLUTIONS

#### A. $D\bar{D}$

Here we study the  $D\bar{D}$  system with different isospin  $I$ . Following the approach introduced in section II, we get the analytical effective interactions between  $D\bar{D}$  in our chiral quark model which are depicted in Fig. 1(a). From Fig. 1(a), one sees that the  $D\bar{D}$  interaction is attractive, especially for isospin  $I = 0$  case. To study if such an attraction is strong enough to bind the  $D\bar{D}$  system, we solve the Schrödinger equation with the programs developed in Refs. [28, 29], and list the obtained binding energies in Table I. Because the mass difference between  $D\bar{D}$  and  $D^*\bar{D}^*$  is not very large, we also consider the coupled effect of  $D^*\bar{D}^*$  on  $D\bar{D}$ . We carry out a perturbative calculation to see the contributions of the off-diagonal elements of this coupled channel to the binding energies of  $D\bar{D}$  and list them in Table I. From Table I, we see there is only one  $I^G(J^{PC}) = 0^+(0^{++})$   $S$ -wave  $D\bar{D}$  bound state with a binding energy 3–35 MeV in our chiral quark model.

TABLE I: The binding energy and the root of mean square radius of  $D\bar{D}$  binding system. The binding energy is listed in such a way: B+ $\Delta$ B, B is the binding energy deduced in the single channel calculation and  $\Delta$ B is the perturbation correction value deduced from the off-diagonal elements of the coupled channel of  $D\bar{D}$  and  $D^*\bar{D}^*$ .

$\chi$ -SU(3) QM			Ex. $\chi$ -SU(3) QM			
			$g_{chv} = 2.351, f_{chv} = 0$		$g_{chv} = 1.973, f_{chv} = 1.315$	
	B+ $\Delta$ B(MeV)	$r_{rms}$ (fm)	B+ $\Delta$ B(MeV)	$r_{rms}$ (fm)	B+ $\Delta$ B(MeV)	$r_{rms}$ (fm)
$I = 0$	1.0+2.3	3.7	33.3+1.4	1.0	21.6+0.2	1.1
$I = 1$	—	—	—	—	—	—

Further analysis shows that the  $D\bar{D}$  interaction is dominated by  $\sigma$ ,  $\sigma'$ ,  $\omega$  and  $\rho$  exchanges. For the  $I=0$  case, in the chiral SU(3) quark model, both  $\sigma$  and  $\sigma'$  exchanges provide attractive interactions, so the total interaction is strong enough to form a  $D\bar{D}$  bound state. In the extended chiral SU(3) quark model, the contributions of vector meson exchange are also included, and  $\rho$  and  $\omega$  exchanges provide additional attraction. Therefore, the  $D\bar{D}$  system has a larger binding energy as shown in Table I. We see that the perturbative contribution of the coupled channel is not very large compared to the results of the single channel and wouldn't obviously change the main feature of the binding solution. The radii of  $D$  and  $\bar{D}$  both are about  $0.54 fm$  in the chiral SU(3) quark model and  $0.49 fm$  in the extended chiral SU(3) quark model (since  $\omega$  is different in the two models), and we find that the rms radius of this  $0^+(0^{++})$   $D\bar{D}$  bound state is bigger than the sum of the radii of  $D$  and  $\bar{D}$ , so we conclude that this  $D\bar{D}$  could form a molecule and this  $0^+(0^{++})$   $D\bar{D}$  molecular state has a mass 3695–3726 MeV. For the  $I = 1$  case, in the chiral SU(3) quark model,  $\sigma$  exchange provides attraction but  $\sigma'$  exchange provides repulsion, thus the total attractive interaction

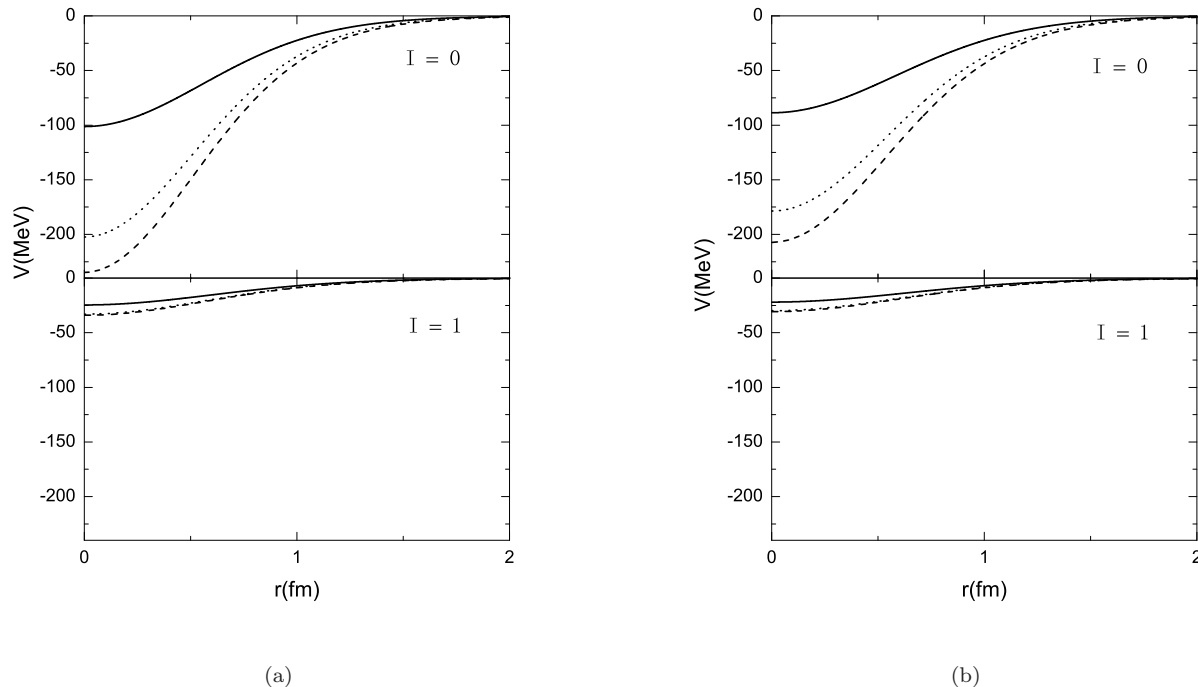


FIG. 1: The total interaction potential of  $D\bar{D}$  and  $B\bar{B}$  systems. 1(a) the total interaction of  $D\bar{D}$  system and 1(b) the total interaction of  $B\bar{B}$  system. The solid, dashed and dotted lines represent the results obtained from the chiral SU(3) quark model, the extended chiral SU(3) quark model without and with the tensor coupling of vector field, respectively.

is too weak to make a  $D\bar{D}$  bound state. In the extended chiral SU(3) quark model, the additional attraction provided by  $\omega$  exchange and the additional repulsion provided by  $\rho$  exchange almost cancel each other, as a result, the total interaction of all the meson exchanges is still too weak to bind  $D\bar{D}$ . Thus, no  $1^-(0^{++})$   $D\bar{D}$  bound state can be obtained due to the insufficiency of the attraction.

## B. $B\bar{B}$

TABLE II: The binding energy and the root of mean square radius of  $B\bar{B}$  binding system. The binding energy is listed in such a way:  $B+\Delta B$ ,  $B$  is the binding energy deduced in the single channel calculation and  $\Delta B$  is the perturbation correction value deduced from the off-diagonal elements of the coupled channel of  $B\bar{B}$  and  $B^*\bar{B}^*$ .

	$\chi$ -SU(3) QM		Ex. $\chi$ -SU(3) QM			
	B+ $\Delta B$ (MeV)	$r_{rms}$ (fm)	$g_{chv} = 2.351, f_{chv} = 0$		$g_{chv} = 1.973, f_{chv} = 1.315$	
			B+ $\Delta B$ (MeV)	$r_{rms}$ (fm)	B+ $\Delta B$ (MeV)	$r_{rms}$ (fm)
$I = 0$	19.2+1.2	0.9	81.8+11.3	0.6	64+2.6	0.6
$I = 1$	—	—	—	—	—	—

Considering the resemblance between  $D\bar{D}$  and  $B\bar{B}$ , the one meson exchange interaction potentials should have similar properties. In our calculation we find the total interaction potential of  $B\bar{B}$  system is also attractive, as shown in Fig. 1(b). By Solving the Schrödinger equation and considering the perturbative correction of the coupled channel of  $B^*\bar{B}^*$  to the binding energies of  $B\bar{B}$ , we list our results in Table II. We notice our results are similar to the ones of Liu *et al.* [17]. It should be emphasized that the  $B\bar{B}$  system is easier to form a bound state than the  $D\bar{D}$  system, because  $B\bar{B}$  system has a much heavier reduced mass 2640 MeV than that of  $D\bar{D}$  system of 932 MeV. We also find that the radii of  $B$  and  $\bar{B}$  are both about  $0.52fm$  in the chiral SU(3) quark model and  $0.46fm$  in the extended chiral SU(3) quark model. However, according to Table II we see that the rms radius of this  $B\bar{B}$  bound state is smaller

than the sum of the radii of  $B$  and  $\bar{B}$ . This feature means  $B$  and  $\bar{B}$  are overlapped with each other, and this  $0^+(0^{++})$   $B\bar{B}$  bound state seems not a molecular state but might be a tetra-quark state with a mass 10467-10540 MeV in our chiral quark models.

#### IV. SUMMARY

In this work, we have studied the bound state problem of  $D\bar{D}$  and  $B\bar{B}$  systems with an analytical effective interaction potential in our chiral quark model. We find only one  $0^+(0^{++})$   $D\bar{D}$  molecule could exist with a mass 3695–3726 MeV, agreeing with the predictions of Refs. [2–10, 17]. For the  $0^+(0^{++})$   $B\bar{B}$  system, they are bound even deeper than the  $D\bar{D}$ , however, the small rms radii mean the overlap is sizeable and, therefore, it may not be interpreted as molecular states, but a tetra-quark state.

We expect future experimental measurements would test the results of our chiral SU(3) quark model and the extended chiral SU(3) quark model. Since our calculation shows the important role of the vector meson exchange, we hope that the future measurement could recognize whether vector meson-exchange or one-gluon-exchange dominates the short range interaction between quarks.

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